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TECHNICAL REPORT 233-5

MECHANICAL PROPERTIES OF METALS AND THEIR CAVITATION DAMAGE RESISTANCE

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NOTATION

S_e^*	Estimated strain energy
T	Ultimate tensile strength
ϵ	Ultimate elongation
Y	Yield strength
S_e'	True strain energy
n	Strain hardening factor
T_f'	True fracture strength
ϵ_f	Elongation at fracture
I	Intensity of cavitation damage
r	Rate of volume loss
A_e	Area of erosion
S_e	Strain energy
r'	Correlation factor
a	Amplitude

SUMMARY

Detailed investigations with a magnetostriction apparatus were carried out to determine the cavitation damage resistance of eleven metals in distilled water at 80°F. The cavitation damage resistance is defined as the reciprocal of the rate of volume loss for a given metal. Among the mechanical properties investigated (ultimate tensile strength, yield strength, ultimate elongation, Brinell hardness, modulus of elasticity and strain-energy), the most significant property which characterizes the energy absorbing capacity of the metals, under the repeated, indenting loads due to the energy of cavitation bubble collapse in the steady state zone, was found to be the fracture strain energy of the metals. The strain energy is defined as the area of the stress-strain diagram up to fracture. The correlation between the strain energy and the reciprocal of the rate of volume loss leads directly to the estimation of the intensity of cavitation damage; this intensity varies as the square of the displacement amplitude of the specimen. All these conclusions are limited to the steady state zone of damage.

INTRODUCTION

Since the work of Parsons (1) in 1919 and Föttinger (2) in 1926, there have been many attempts to characterize the cavitation damage resistance of materials by a single, common mechanical property. Although Honegger (3), in 1927, did not find any correlation between hardness and erosion resistance, Gardner (4), in 1932, found that the hardness of a metal was the principal property in determining the resistance to erosion. Many more references may be cited to bring out similar controversies with regard to other mechanical properties such as yield strength, ultimate tensile strength, ultimate elongation and modulus of elasticity. One can get a clear picture of the magnitude of the conflicts in this area from some of the excellent review articles in the technical literature (5,6,7).

These controversies are a result of an inadequate understanding of the mechanism of cavitation damage. Recent advances in this direction have made it possible to rationalize some of the conflicts, and to propose a mechanical property that most significantly characterizes the cavitation damage resistance of metals in the absence of corrosion. It is the purpose of this paper to develop the logic behind such an argument, and to present recent substantiating experimental evidence.

One of the basic parameters involved in the testing of materials for cavitation damage resistance is the test duration. The rate of loss of material depends upon the test duration itself even though every other test parameter is maintained precisely constant. Recent analysis showed that there exist four zones of damage with respect to testing time. They are:

1. Incubation Zone
2. Accumulation Zone
3. Attenuation Zone
4. Steady State Zone

A detailed discussion of these zones appears elsewhere (14). All the results and conclusions presented herein are limited to the steady state zone of damage in which the rate of damage does not change with time.

MECHANISM OF CAVITATION DAMAGE

It is now generally established that the bubble collapse energy produces indentations on the metal as shown in Figure 1. The indentations may be produced on the material either by the impingement of jets or by shock waves. The evidence in support of these methods of dent formation is abundant in the literature (8,9,10,11,12). In the absence of corrosion, it is quite reasonable to proceed on the assumption that these dents, formed by mechanical means, are the main cause of fracture and loss of metal.

When such repeated, indenting forces or blows act upon a metallic surface, one of the following events may occur depending upon the intensity of impact:

(i) There may not be any permanent deformation;

(ii) The metal may deform after a certain number of repetitive blows;

(iii) A permanent deformation may develop at the onset of the first blow; and

(iv) The metal may 'splash' and 'wash-out' on the first blow itself or after a certain number of repetitions.

These possibilities can be readily understood from Figure 2 which shows schematically the variation of the internal friction of metals with strain amplitude in the case of repeated loadings. In the case of cavitation damage, it is reasonable to assume, for the sake of the present argument, that the energy of collapse for a given frequency, amplitude, and liquid varies in a statistical manner as shown by the hypothetical distribution in Figure 3. As the strain amplitude is increased, the mean strain may increase, the mean number of bubbles possessing adequate energy of collapse to produce this strain may increase, or both of these possibilities may occur. In any case, the response of a metal to a given strain can be qualitatively explained by an equivalent indentation fatigue diagram as shown in Figure 4. Accordingly, the response of a metal to a cavitation damage test is dependent upon the order of magnitude of the strain. In Figure 4 three regions have been designated to point out the possible material responses to indentation events discussed previously. Photographs of the metallic surfaces which exhibited the response of each region are also shown.

With the above physical picture in mind, let us pose the question: What is the characteristic property of a metal that controls the eroded volume as a result of this mechanical process? Obviously this property is the energy absorbing capacity per unit volume of the metal up to fracture when subjected to the repeated overlapping indentations. At the present state of knowledge, there is no way to determine this quantity exactly. For this reason, several investigators have tried to correlate this quantity with most of the commonly known mechanical properties of metals.

Our superficial intuition initially suggests that the hardness of the surface may be of utmost importance. However, when the physical meaning of hardness is examined critically, we find that indentation hardness is essentially a measure of the yield stress of the material (13). It does not represent the full measure of the energy required for fracture because it neglects the elongation of the material up to its ultimate strength. Similar arguments can be advanced against other mechanical properties such as yield stress, ultimate stress and others. An earlier attempt to correlate the area of the stress-strain diagram up to fracture and the cavitation damage rate proved to be encouraging (12). The present investigation is an extension of this attempt in a more detailed manner and confirms the earlier results.

EXPERIMENTAL FACILITY AND TECHNIQUE

The HYDRONAUTICS, Incorporated Magnetostriction Apparatus was used for these investigations. The details of the equipment and the experimental procedure are outlined in Reference 14. A double cylinder velocity transformer replaced the exponential horn. In Figure 5 are shown the essential test parameters of the magnetostriction apparatus. Simple flat specimens were tested in distilled water at 27°C (approximately).

RESULTS AND DISCUSSION

Metals Tested and Their Mechanical Properties

The following metals were tested.

Group 1.

(i) 1100-O Aluminum

(ii) Cast Iron

(iii) Molybdenum

(iv) 410 Stainless Steel

(v) 304-L Stainless Steel

Group 2.

(i) 1100-F Aluminum

(ii) 2024-T4 Aluminum

(iii) 1020 Mild Steel

(iv) Tobin Bronze

(v) Monel

(vi) 316 Stainless Steel

For the materials listed under Group 1, the mechanical properties were obtained from the literature. The typical values in the references varied over a range as shown in Table 1. These values are available only for the common properties such as yield strength, ultimate strength, ultimate elongation, Brinell hardness and modulus of elasticity. Even typical stress-strain diagrams are a rarity in the literature for these metals. Further, it should be realized that these properties vary from heat to heat for the same material. However, a preliminary attempt was made to correlate the cavitation damage resistance with these mechanical properties. For this purpose, the strain energy was roughly estimated from the following relationship

$$S_e^* = (T + Y)\,\frac{\epsilon}{2} \qquad [1]$$

where

S_e^* is the estimated strain energy,

T is the ultimate tensile strength,

ϵ is the ultimate elongation, and

Y is the yield strength.

This relationship was used since the values of T, Y and ϵ were readily available and gives an approximate value of the area of the stress-strain diagram, assuming it to be a trapezoid. Among the properties considered in this preliminary analysis, the best correlation was obtained with this estimated strain energy as shown in Figure 6. Since T, Y and ϵ vary over a wide range, the estimated value of the strain energy also varies over a range; this range is shown in Figure 6 by a solid line for each material, while the mean value is shown by a solid circle. This analysis revealed the need for additional test data.

The second group of six metals was selected for actual tests and detailed analysis. The engineering stress-strain diagrams were obtained from the same bar stock of material from which the cavitation test specimens were machined. The stress-strain diagrams for these six materials are given in Figure 7. These data were obtained according to the Federal Test Method Standard TT-, No. 151a with half an inch diameter tensile specimens of two inch gauge length (15). The true stress-strain diagrams for the six metals are shown in Figure 8. The strain energy was computed by the following three methods:

1. Area of the true stress-strain diagram given by the relationship

$$S_e' = \left(\frac{1}{1+n}\right) T_f' \epsilon_f \qquad [2]$$

where

S_e' is the true strain energy,

n is the strain hardening factor,

T_f' is the true fracture strength, and

ϵ_f is the elongation at fracture.

2. Area of the engineering stress-strain diagram obtained by direct measurement.

3. An approximate estimation according to Equation [1].

The reason for employing these three methods is to determine the percentage deviation among the three strain energy values.

The mechanical properties of the second group of six metals, obtained by actual tests, are listed in Table 2. However, the Brinell hardness values shown in this table are typical values reported in the literature. It can be seen that the strain energy values computed by the above three methods agree closely, within ±10 percent, with the true strain energy as the standard.

Cavitation Damage Resistance

All of these metals were tested for their cavitation damage resistance according to the procedures outlined in detail in Reference 14. Essentially, the procedure is to test each of the metals under a given set of experimental conditions through the four zones of damage, namely, incubation zone, accumulation zone, attenuation zone and steady state zone. It is of interest to note that all the metals which were tested exhibited these zones. The specimen that had reached the steady state zone was used to obtain the relationship between the rate of volume loss and the displacement amplitude as shown in Figure 9. The reciprocal of the rate of volume loss is defined as the cavitation damage resistance of a material. The cavitation damage resistance at a given amplitude (2×10^{-3} cm) in the steady state zone was plotted against the various mechanical properties of the metals as shown in Figures 10 through 15. The mechanical properties considered here are strain energy, ultimate tensile strength, yield strength, Brinell hardness, ultimate elongation and modulus of elasticity. Both groups of metals have been included for this correlation. The values of linear correlation factor for each of the above mechanical properties are tabulated below.

Mechanical Property	Correlation Factor
Strain Energy	0.91
Ultimate Strength	0.79
Yield Strength	0.65*
Brinell Hardness	0.51
Modulus of Elasticity	0.49
Ultimate Elongation	0.48

The correlation factor, r', for two variables, x and y, is calculated from the following formula:

$$r' = \frac{n\epsilon_{xy} - \epsilon_x \epsilon_y}{\sqrt{\left[n\epsilon_x{}^2 - \left(\epsilon_x\right)^2\right]\left[n\epsilon_y{}^2 - \left(\epsilon_y\right)^2\right]}}$$

where

n is the number of points in an x, y plane.

---

* This is based on ten sample points since the yield strength for cast iron is not available.

This analysis clearly shows that the most significant linear correlation is obtained with the strain energy of the material. It follows from this result that the energy absorbing capacity of a metal characterizing the cavitation damage resistance is largely determined by the strain energy.

Limitations

1. This analysis is confined to six common properties of metals. It is not implied that there is no other property more significant than strain energy.

2. This analysis is limited to the steady state zone. In the earlier zones, the interaction of the strain hardening exponent and the surface roughness will have to be taken into account.

3. No superposition of a corrosive environment is considered in this analysis. The interaction of a corrosive environment on the fatigue properties of metals is important.

Intensity of Cavitation Damage

One of the immediate uses of this correlation is to estimate the intensity of cavitation damage as a function of displacement amplitude. The intensity has been defined as the power absorbed per unit area of the material (16) and is given by

$$I = \frac{r.S_e}{A_e} \qquad [3]$$

where

I is the intensity of cavitation,

r is the rate of volume loss,

A_e is the area of erosion, and

S_e is the strain energy.

It can be seen that the intensity of cavitation damage for a given amplitude is given by the reciprocal of the slope of the line in Figure 10 divided by the area of erosion. The best fit lines by the least square method for each amplitude are shown in Figure 16. The intensity, thus computed, varies as the square of the amplitude for the experimental conditions in the steady state zone (Figure 17).

CONCLUSIONS

The following conclusions are drawn as a result of these investigations

1. Among the mechanical properties investigated to characterize the energy absorbing capacity of metals under the repeated indentations produced by cavitation damage, the most significant correlation is obtained with the strain energy of the metal, where the strain energy is defined as the area of the stress-strain diagram up to fracture in a simple tensile test. This conclusion is limited to the steady state zone of damage in a non-corrosive environment.

2. The above relationship leads directly to the estimation of the intensity of cavitation damage. According to this estimate the intensity varies as the square of the displacement amplitude in the steady state zone under the present experimental conditions.

ACKNOWLEDGMENTS

This investigation was supported by the Office of Naval Research, Department of the Navy, Contract No. Nonr 3755(00)(FBM) NR 062-293. Many useful discussions with Mr. H. S. Preiser during the course of this work are gratefully acknowledged.

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TABLE 1

Mechanical Properties of Five Metals from Literature

	Ultimate Strength dynes/cm²*		Yield Strength dynes/cm²		Ultimate Elongation		Brinell Hardne		Modulus of Elasticity dynes/cm²
	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	
1100-O-Aluminum	89.6×10^7	-	34.4×10^7	-	45	35	23	-	68.9×10^{10}
Cast Iron	310×10^7	138×10^7	-	-	10	5	265	110	103.3×10^{10}
Molybdenum	792×10^7	469×10^7	689×10^7	310×10^7	42	5	250	200	317×10^{10}
410 Stainless Steel	827×10^7	413×10^7	620×10^7	241×10^7	30	15	300	150	193×10^{10}
304-L Stainless Steel	861×10^7	482×10^7	655×10^7	172×10^7	60	25	280	150	200×10^{10}

* $\frac{\text{dynes}}{\text{sq cm}} = 1.45 \times 10^{-5}$ lbs/sq in.

TABLE 2 - Mechanical Properties of Six Metals from Actual Tensile Tests

Material	Units	Modulus of Elasticity	Yield Strength	Ultimate Tensile Strength	Hardness BHN	Density g/cm^3	True Ultimate Tensile Strength	Strain Hardening Factor	Ultimate Elongation %	True Ultimate Elongation %	True Strain Energy	Engineering Strain Energy	Estimated Strain Energy
316 Stainless Steel	psi	25×10^6	68×10^3	91.4×10^3	160	7.98	12.6×10^4	0.16	44	36	39.0×10^3	37.0×10^3	35.0×10^3
	$dynes/cm^2$	172×10^{10}	469×10^7	630×10^7			86.8×10^8				269×10^7	255×10^7	241×10^7
Monel	psi	26×10^6	77.9×10^3	97.9×10^3	125	8.84	11.2×10^4	0.088	27	24	24.7×10^3	23.7×10^3	23.7×10^3
	$dynes/cm^2$	179×10^{10}	537×10^7	675×10^7			77.2×10^8				170×10^7	163×10^7	163×10^7
1020 Mild Steel	psi	24×10^6	91.0×10^3	112.6×10^3	130	7.85	14.6×10^4	0.13	12	11.5	14.9×10^3	12.5×10^3	12.2×10^3
	$dynes/cm^2$	165×10^{10}	627×10^7	776×10^7			101×10^8				103×10^7	86.1×10^7	84.1×10^7
Tobin Bronze	psi	12×10^6	57.7×10^3	72.0×10^3	125	8.41	8.3×10^4	0.102	26	23.5	17.6×10^3	17.8×10^3	16.9×10^3
	$dynes/cm^2$	82.7×10^{10}	398×10^7	496×10^7			57.2×10^8				121×10^7	123×10^7	116×10^7
2024 Aluminum	psi	10×10^6	50.4×10^3	70.6×10^3	120	2.70	8.1×10^4	0.143	21.5	19.5	13.8×10^3	13.7×10^3	13.0×10^3
	$dynes/cm^2$	68.9×10^{10}	347×10^7	486×10^7			55.8×10^8				95×10^7	94×10^7	89.6×10^7
1100-F Aluminum	psi	9×10^6	19.8×10^3	22.3×10^3	42	2.70	2.6×10^4	0.065	19.5	17.2	4.2×10^3	3.2×10^3	4.1×10^3
	$dynes/cm^2$	62.0×10^{10}	136×10^7	154×10^7			17.9×10^8				28.9×10^7	22.0×10^7	28.2×10^7

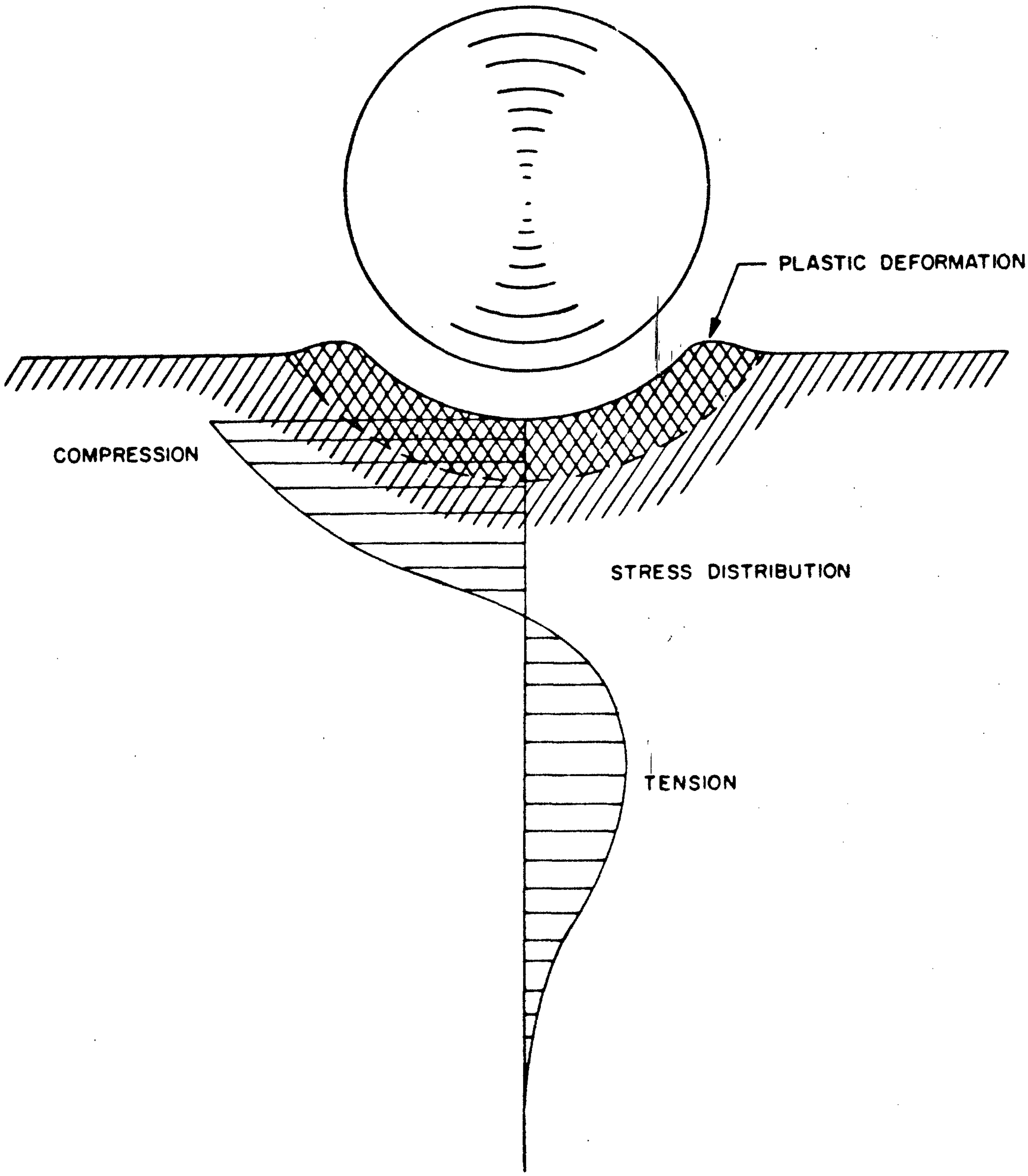


FIGURE 1 -DEFINITION SKETCH FOR DEFORMATION DUE TO CAVITATION BUBBLE COLLAPSE

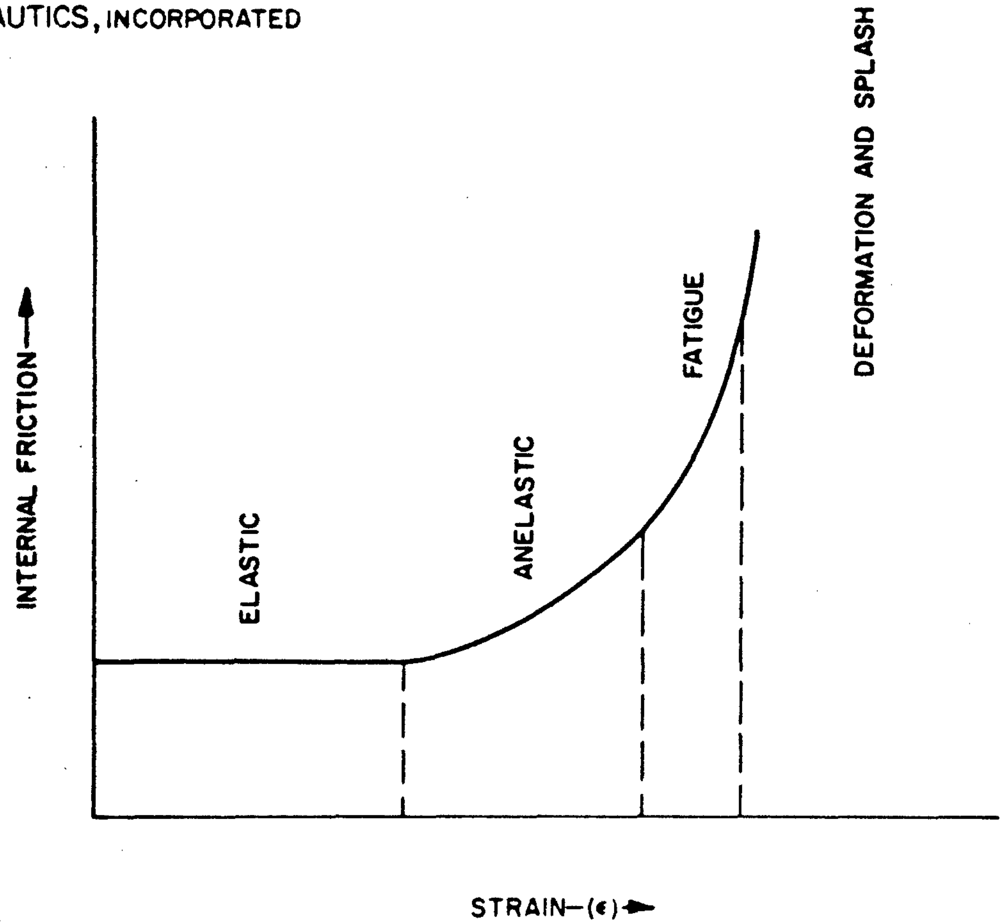


FIGURE 2–SCHEMATIC REPRESENTATION OF THE RESPONSE OF METALS TO REPEATED STRAINING

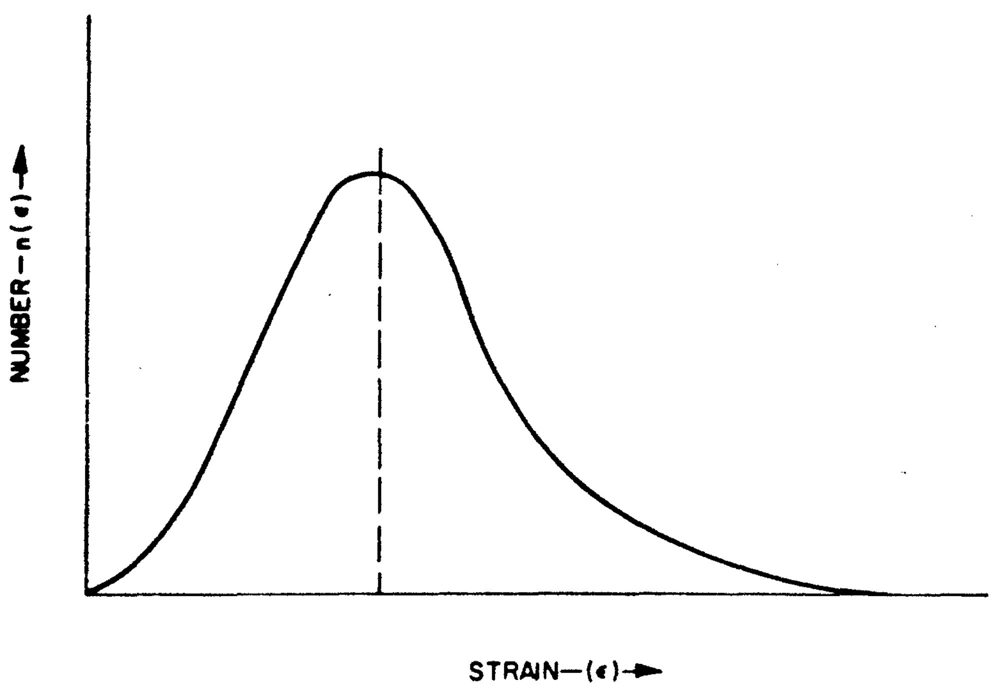
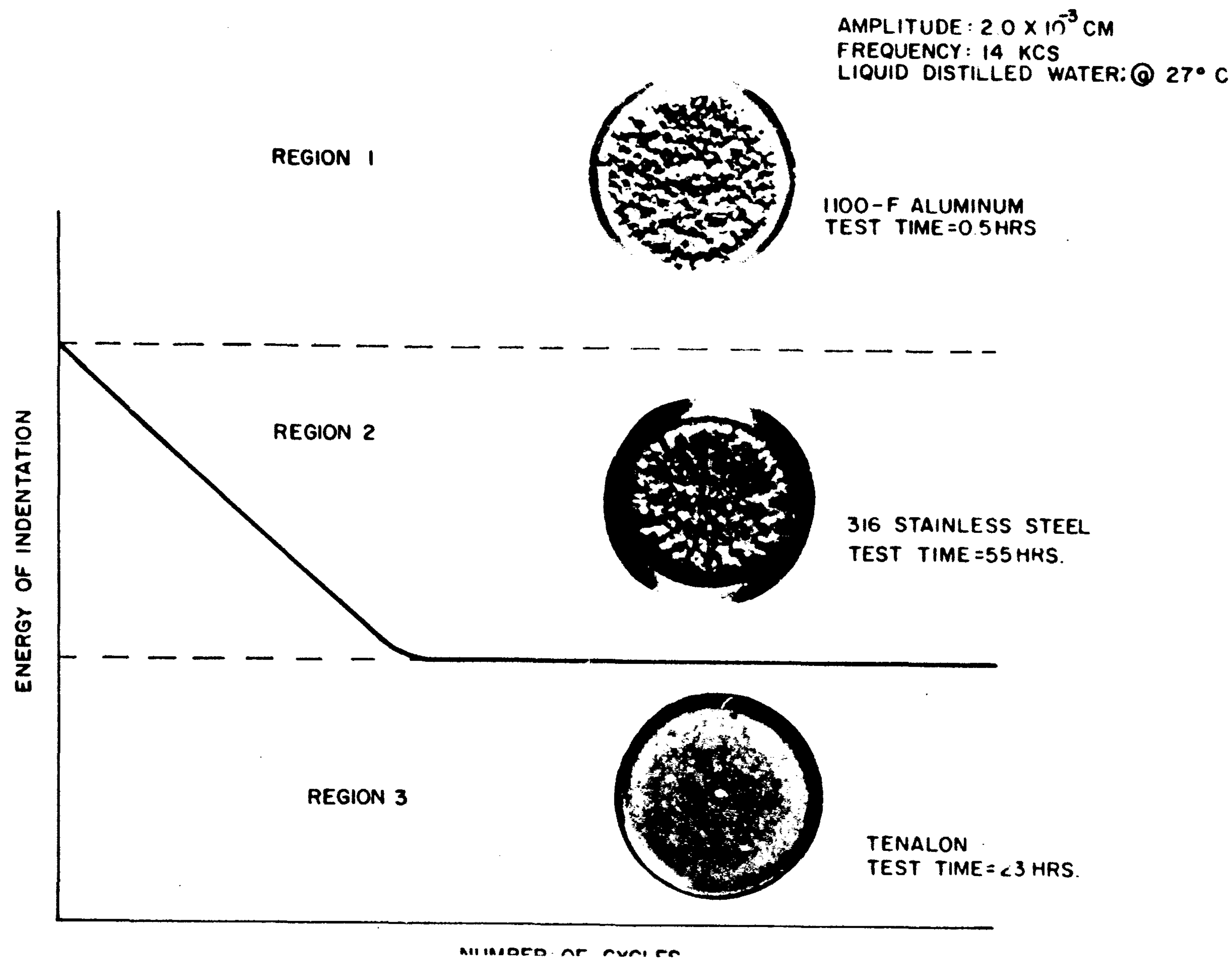


FIGURE 3–HYPOTHETICAL DISTRIBUTION OF STRAINS CAUSED BY THE COLLAPSE OF BUBBLES IN A CAVITY CLOUD


AMPLITUDE: 2.0 X 10^-3 CM
FREQUENCY: 14 KCS
LIQUID DISTILLED WATER: @ 27° C
REGION 1
1100-F ALUMINUM
TEST TIME=0.5HRS
REGION 2
316 STAINLESS STEEL
TEST TIME=55HRS.
REGION 3
TENALON
TEST TIME=<3 HRS.
ENERGY OF INDENTATION
NUMBER OF CYCLES

$f = 14$ KCS
$a = 0.7 \times 10^{-3}$-3.0×10^{-3} CM
$2r = 1.59$ CM
$d \simeq 0.3$ CM
$H \simeq 8.0$ CM
$D \simeq 7.0$ CM
LIQUID: DISTILLED WATER @ 27°C

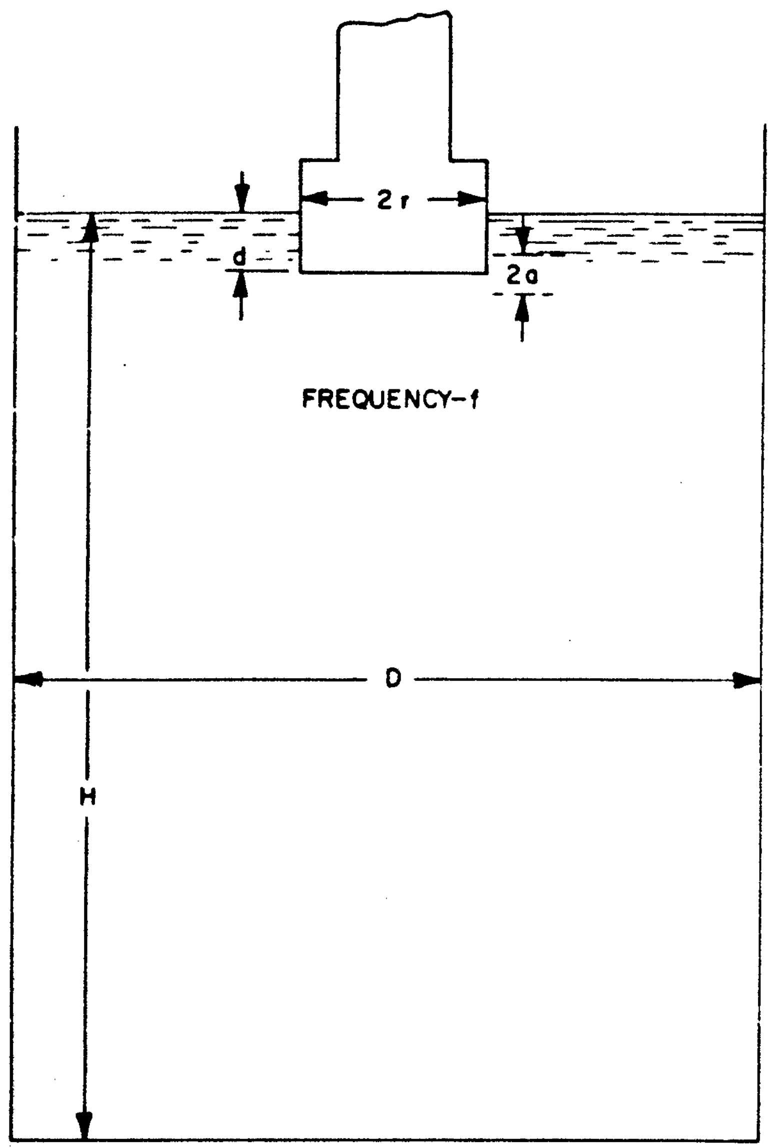


FIGURE 5–DEFINITION SKETCH OF THE MAGNETOSTRICTION DEVICE

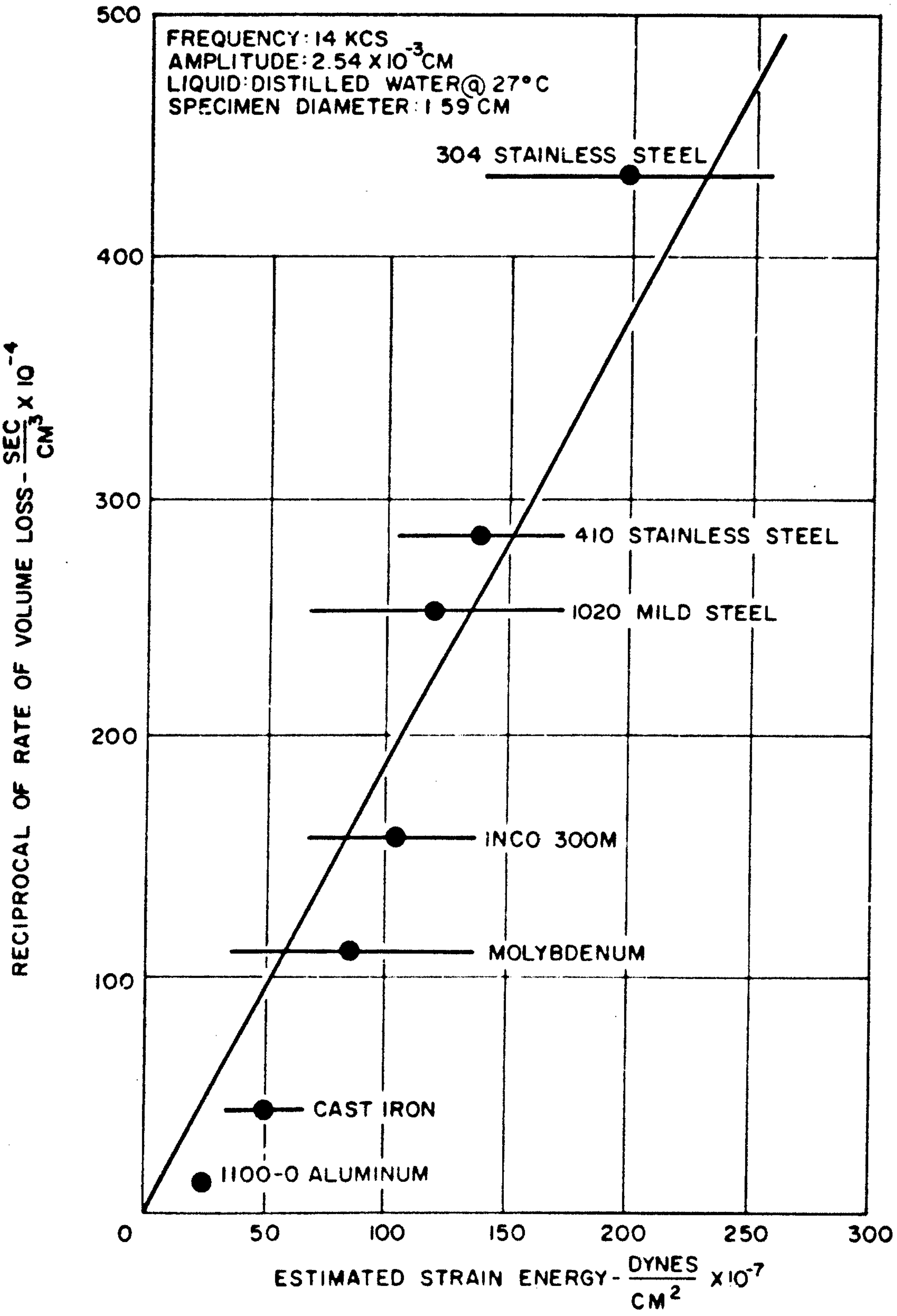


FIGURE 6 - CORRELATION BETWEEN ESTIMATED STRAIN ENERGY AND RECIPROCAL OF RATE OF VOLUME LOSS

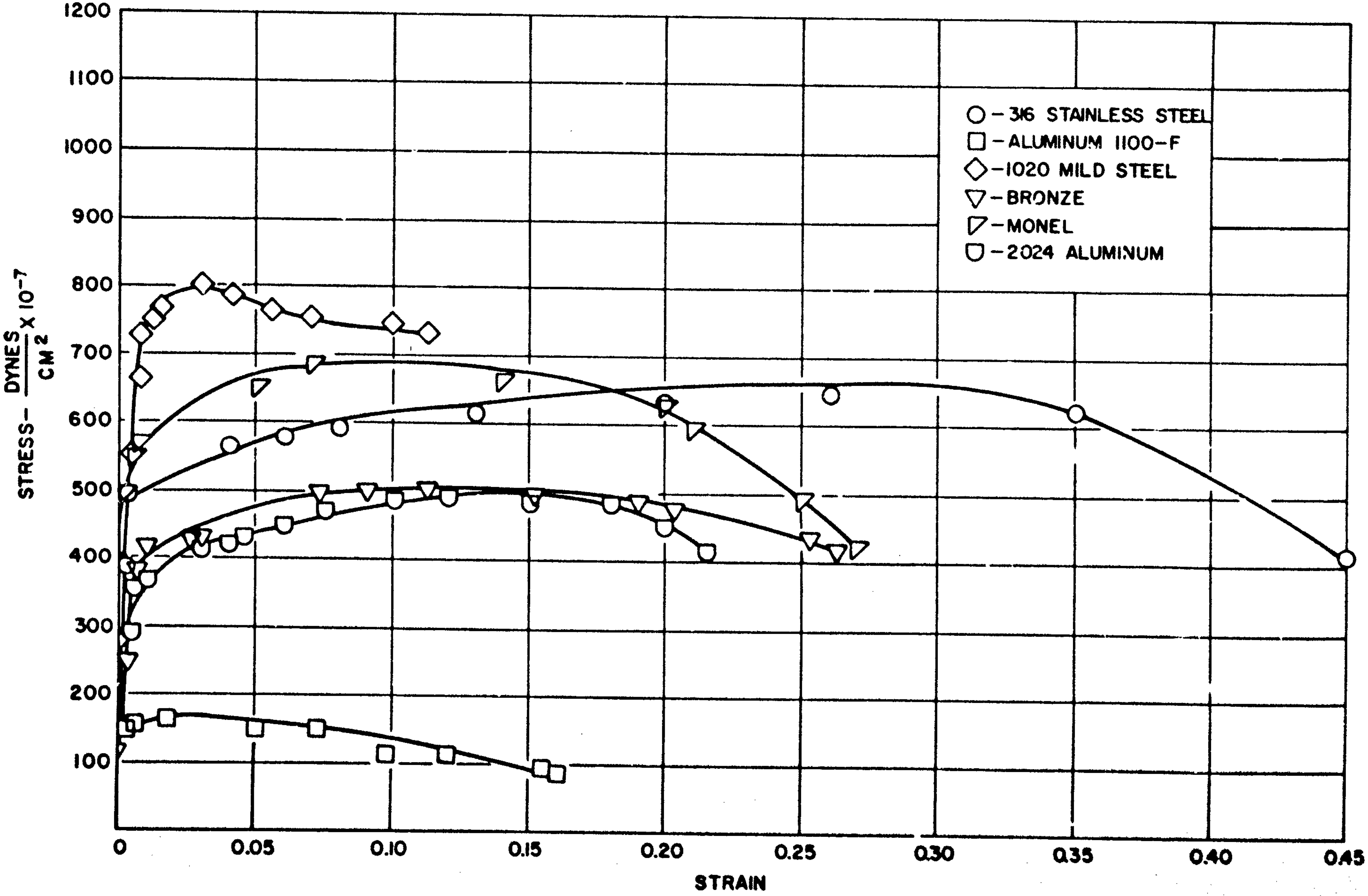
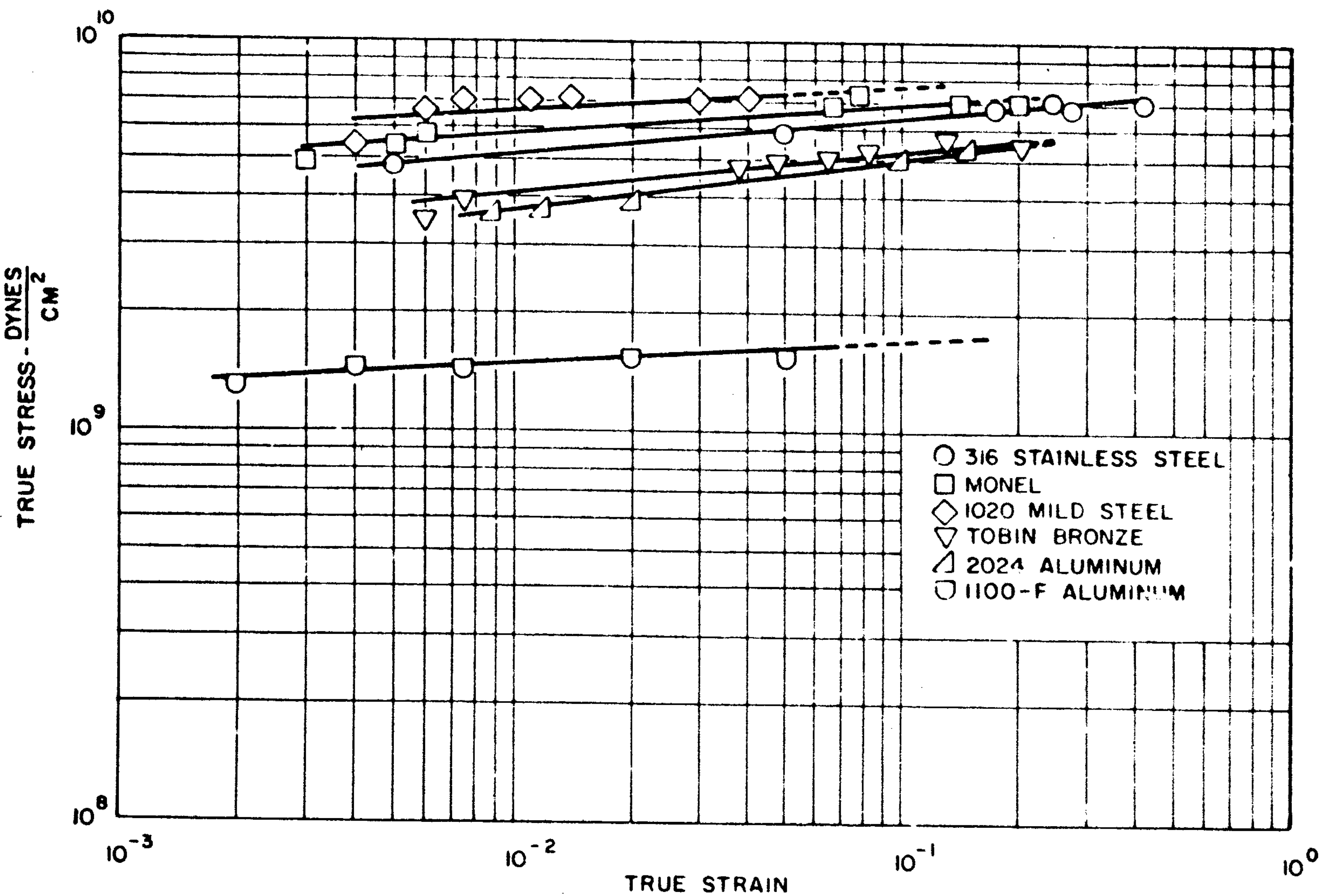


FIGURE 7-ENGINEERING STRESS-STRAIN DIAGRAMS FOR SIX METALS


TRUE STRESS - DYNES/CM²
10¹⁰
10⁹
10⁸
10⁻³
10⁻²
10⁻¹
10⁰
TRUE STRAIN
316 STAINLESS STEEL
MONEL
1020 MILD STEEL
TOBIN BRONZE
2024 ALUMINUM
1100-F ALUMINUM

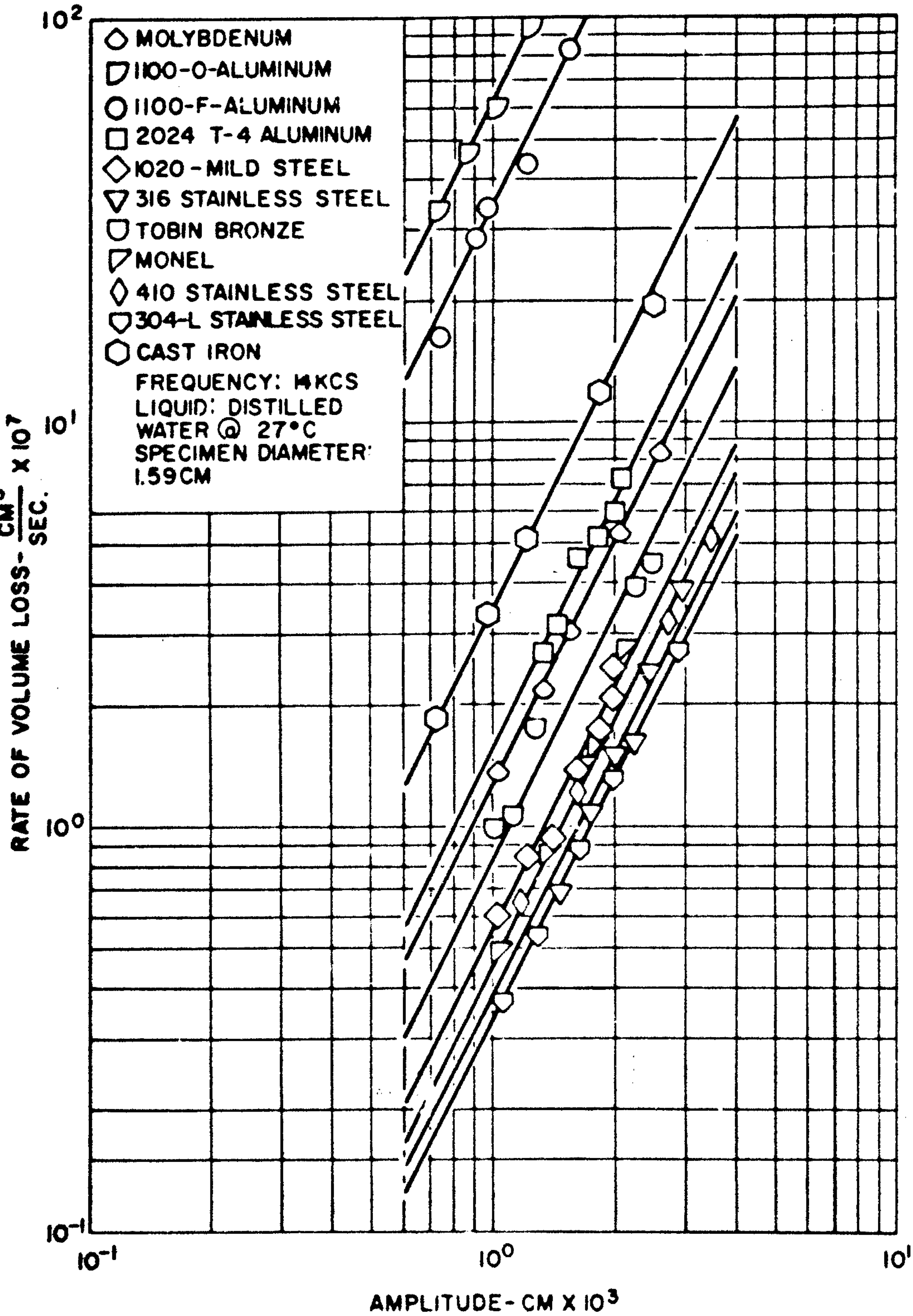


FIGURE 9–EFFECT OF AMPLITUDE ON DAMAGE RATE FOR ELEVEN METALS

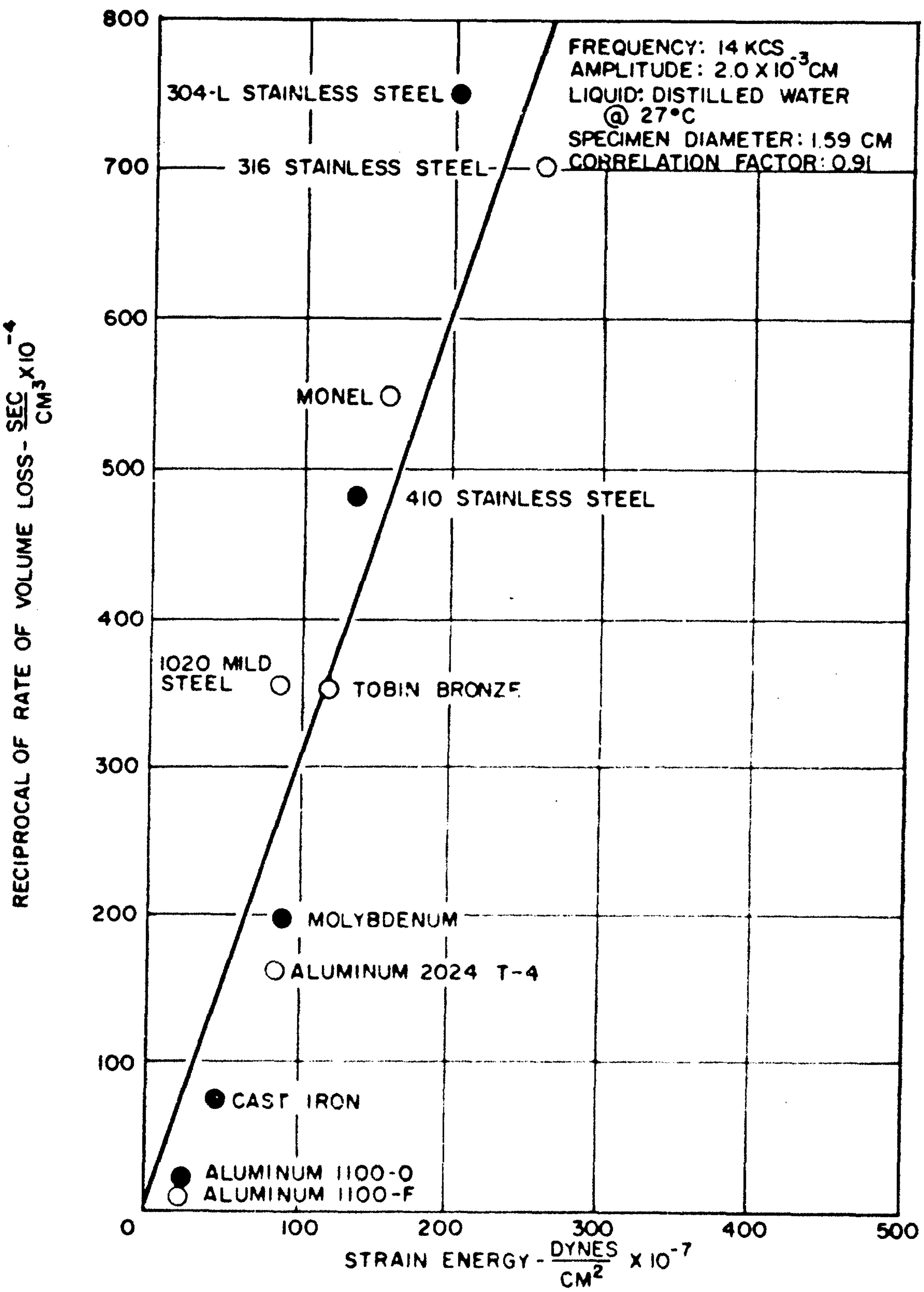


FIGURE 10-CORRELATION BETWEEN STRAIN ENERGY AND RECIPROCAL OF RATE OF VOLUME LOSS

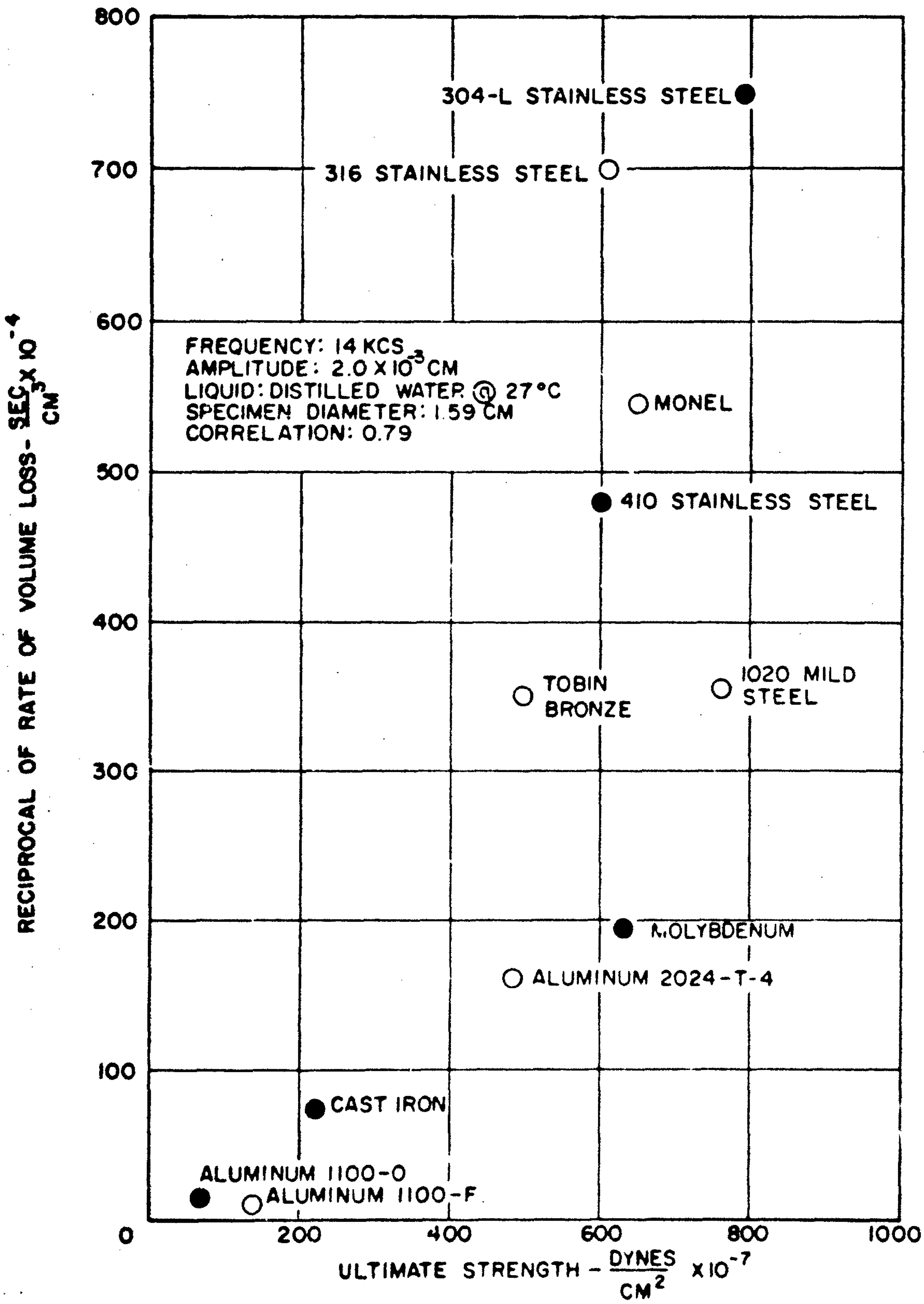


FIGURE 11 - CORRELATION BETWEEN ULTIMATE STRENGTH AND RECIPROCAL OF RATE OF VOLUME LOSS

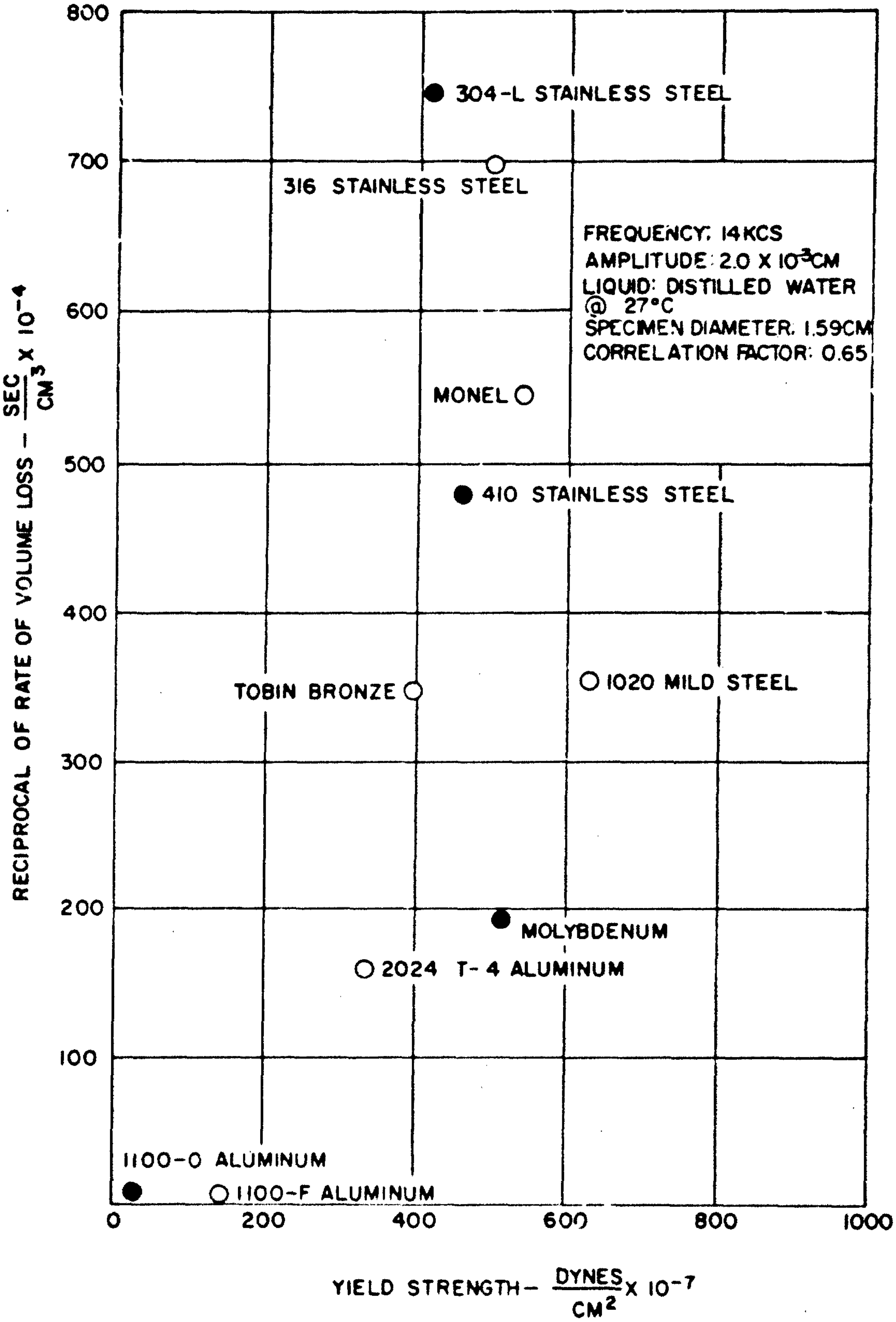


FIGURE 12-CORRELATION BETWEEN YIELD STRENGTH AND RECIPROCAL OF RATE OF VOLUME LOSS

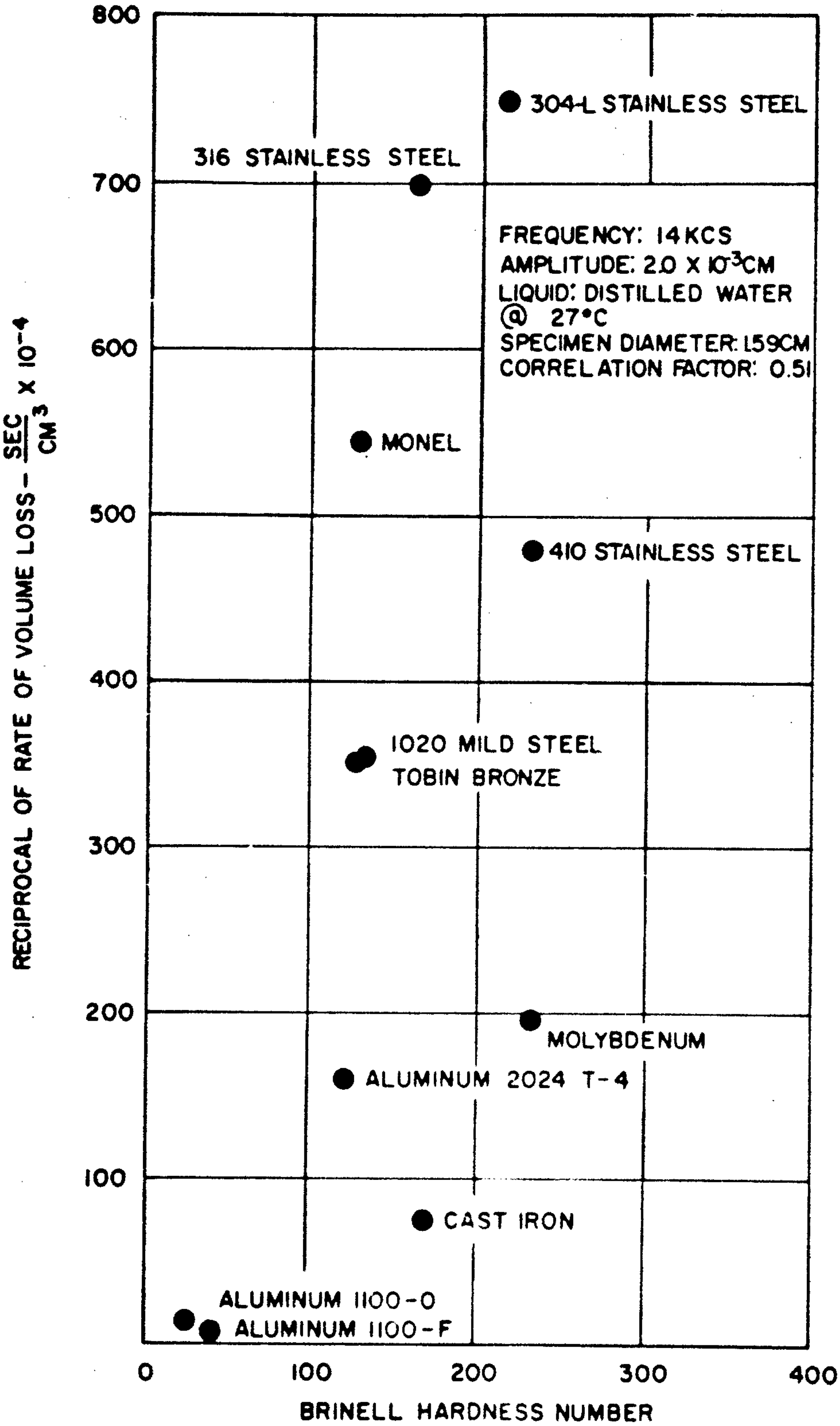


FIGURE 13-CORRELATION BETWEEN BRINELL HARDNESS AND RECIPROCAL OF RATE OF VOLUME LOSS

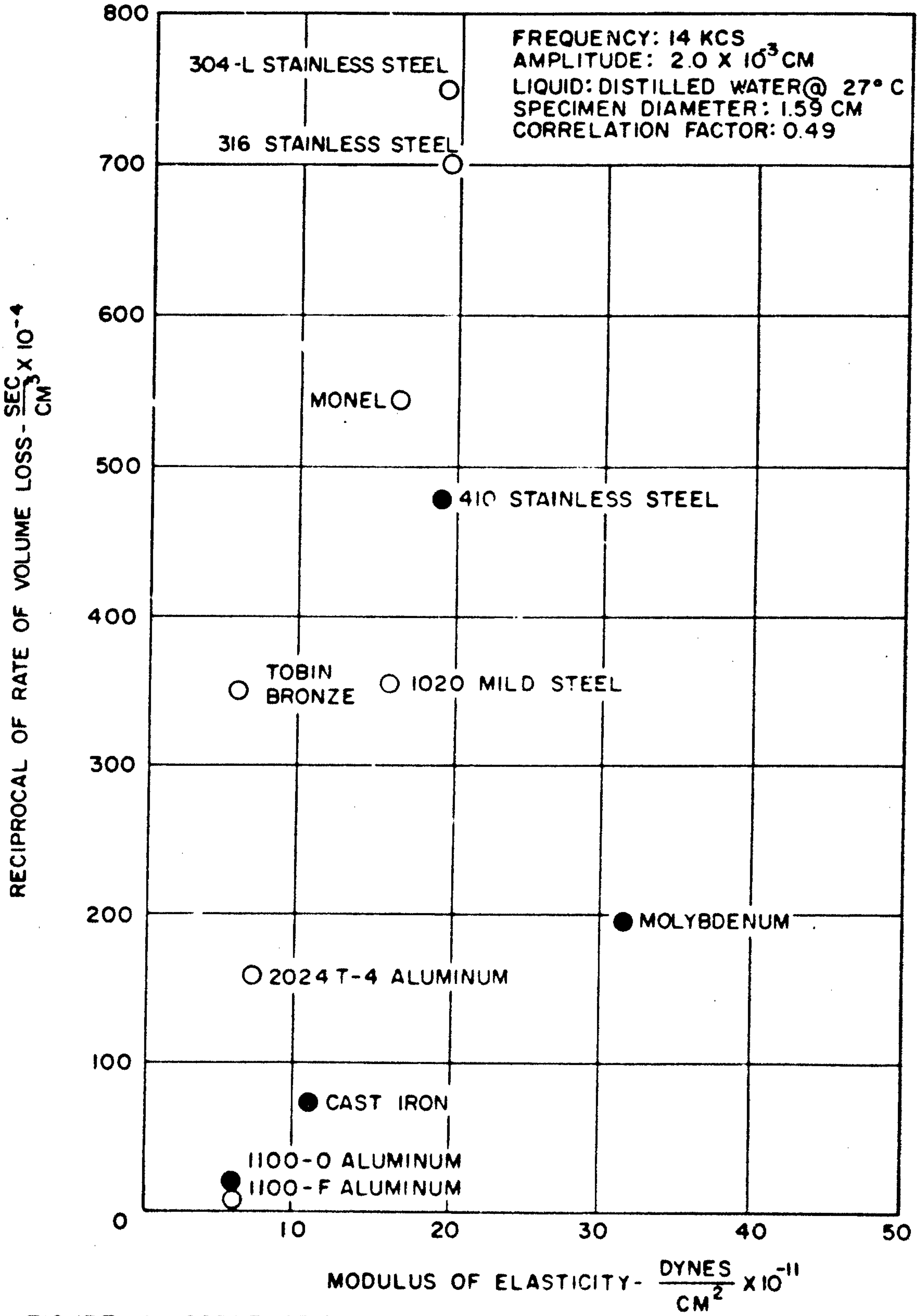


FIGURE 14 - CORRELATION BETWEEN MODULUS OF ELASTICITY AND RECIPROCAL OF RATE OF VOLUME LOSS

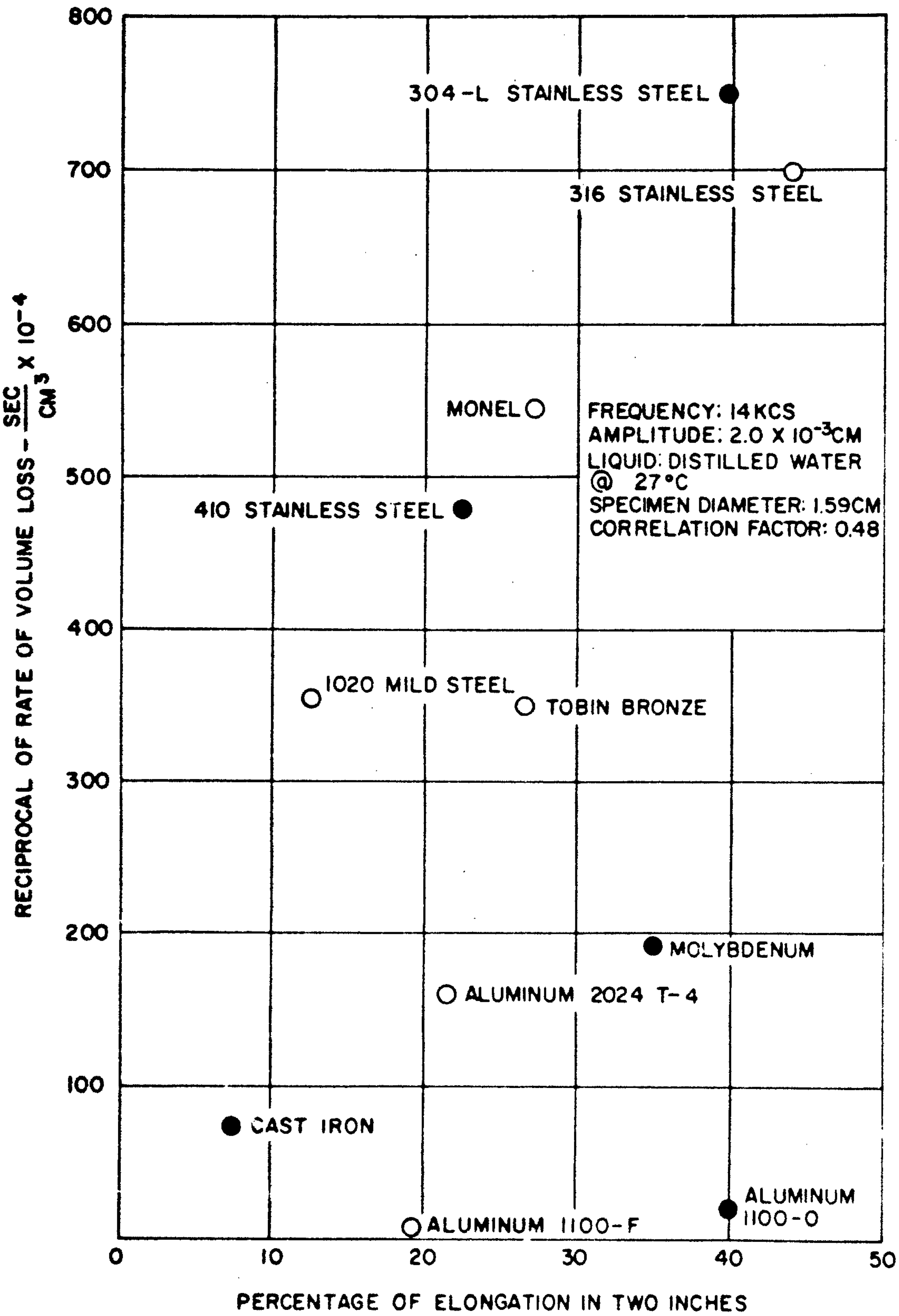


FIGURE 15-CORRELATION BETWEEN ULTIMATE ELONGATION AND RECIPROCAL OF RATE OF VOLUME LOSS

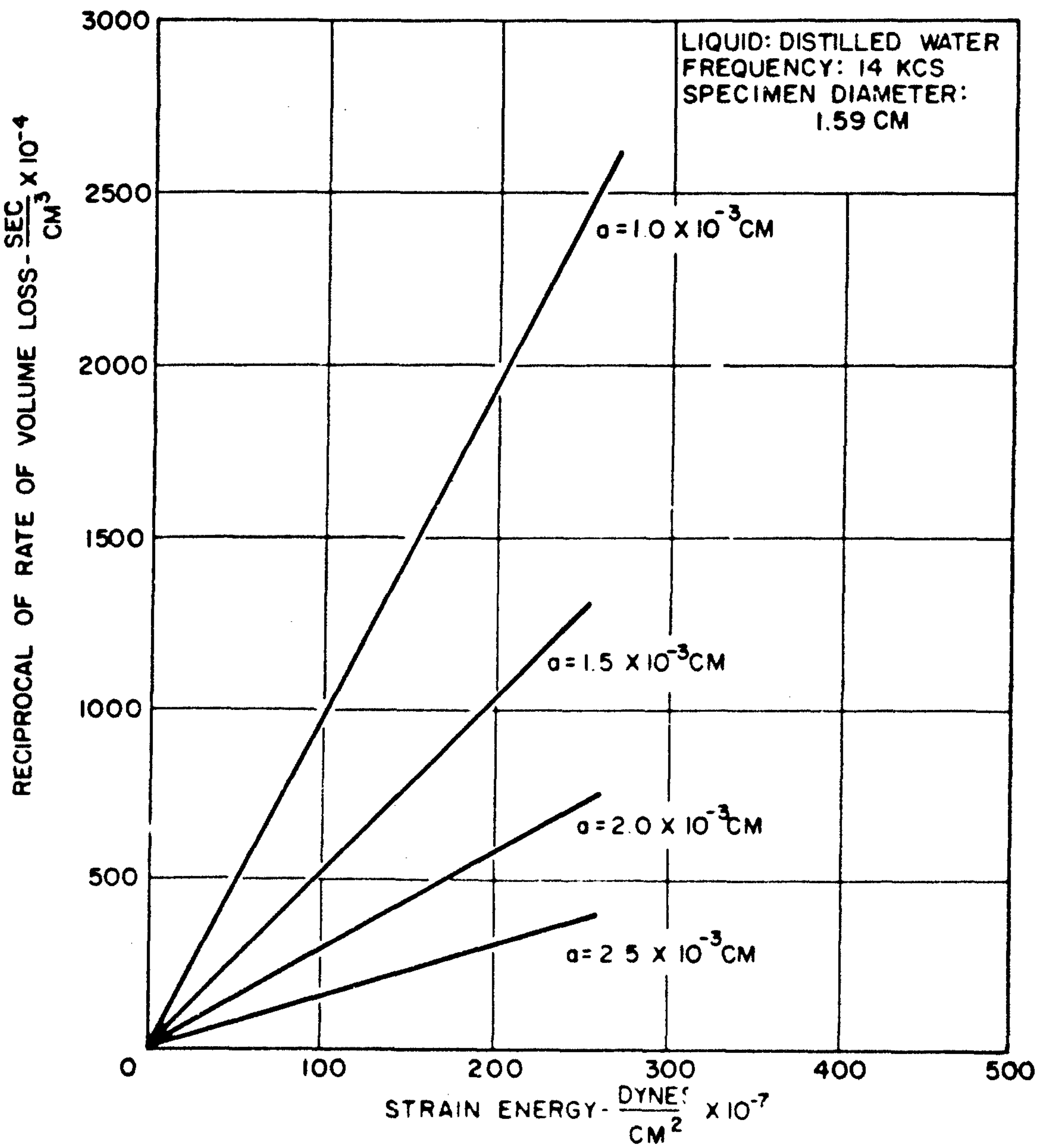


FIGURE 16-RELATIONSHIP BETWEEN STRAIN ENERGY AND RECIPROCAL OF RATE OF VOLUME LOSS AT VARIOUS AMPLITUDES

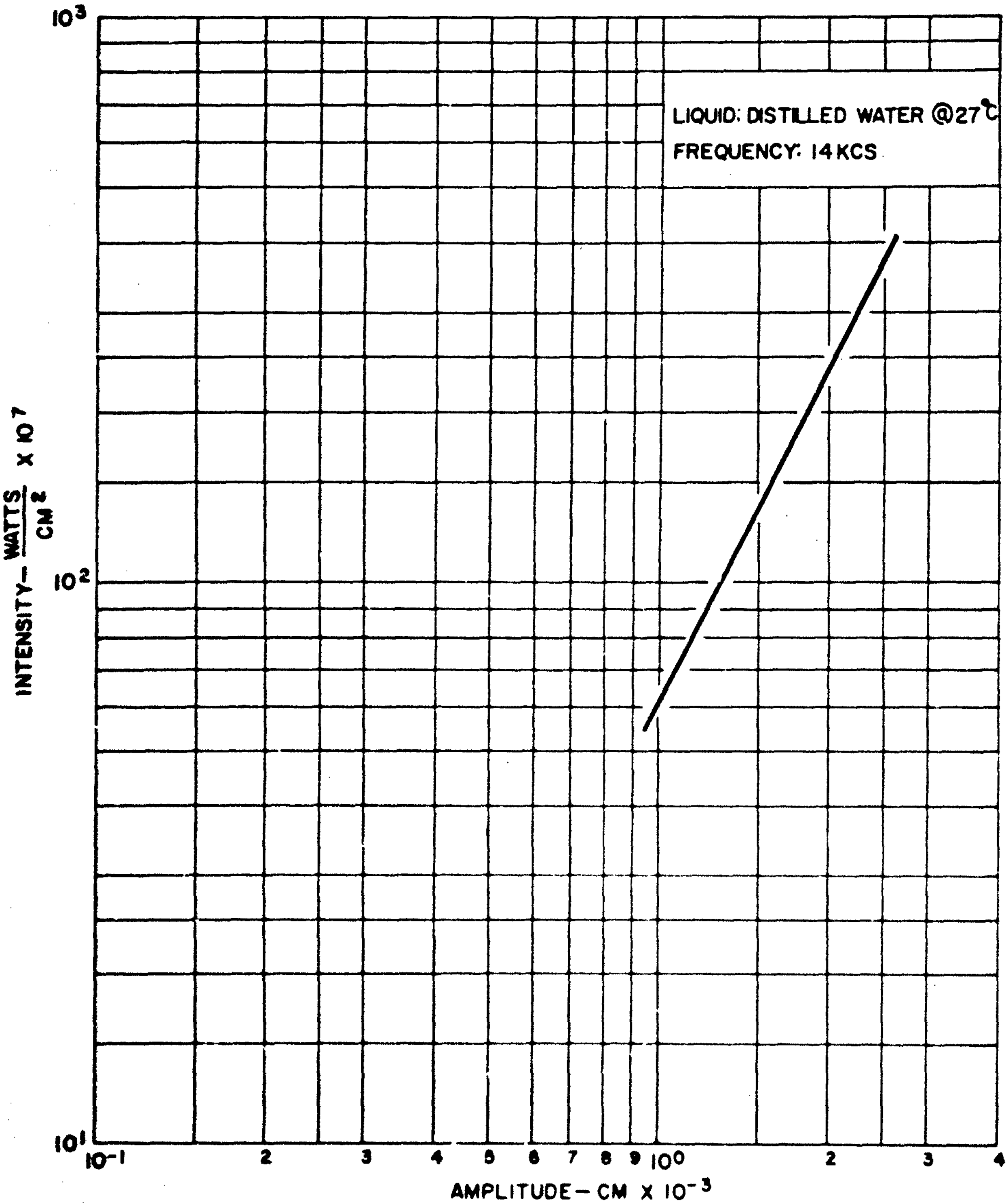


FIGURE 17-EFFECT OF DISPLACEMENT AMPLITUDE ON OUTPUT INTENSITY

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